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THE EVALUATION OF A DEFORMABLE DIFFRACTION GRATING FOR A STIGMATIC EUV SPECTROHELIOMETER

Progress Report for NASA Grant NAGW-540
for the period 15 February to 15 August 1984

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The program to develop a high-resolution, extreme ultraviolet (EUV) spectroheliometer, which was started at the University of Colorado under NASA Grant NAGW-396, was terminated at the University of Colorado on 30 November 1983, and transferred to Stanford University. The program was restarted at Stanford on 15 February 1984, under NASA Grant NAGW-540.

The first six months of the program at Stanford have concentrated on the two key areas of technology that are crucial to the development of the high-resolution EUV spectroheliometer: namely, the elastically deformable toroidal diffraction grating and the open-structure imaging pulse-counting detector system.

In order to verify the optical performance of a high-frequency toroidal grating at EUV wavelengths, a 3600-groove-mm^{-1} master grating on a spherical concave blank has been procured from Hyperfine, Inc., in Boulder, Colorado, by M. C. E. Huber, the co-investigator at the Institute for Astronomy in Zurich, using Swiss Federal Institute of Technology funds. This grating has been successfully replicated onto a deformable metal blank fabricated for Huber by Lemaître and his collaborators at Marseilles (see Figure 1). The master grating was replicated onto the metal blank when it was in a relaxed spherical condition. After replication, the sub-master grating was elastically deformed into the appropriate toroidal form for stigmatic imaging in first order at a wavelength near 600 Å. With the grating in its toroidal form, a replica grating was fabricated on a fixed toroidal blank for the initial optical evaluation. This grating was osmium coated for high reflectivity at EUV wavelengths.

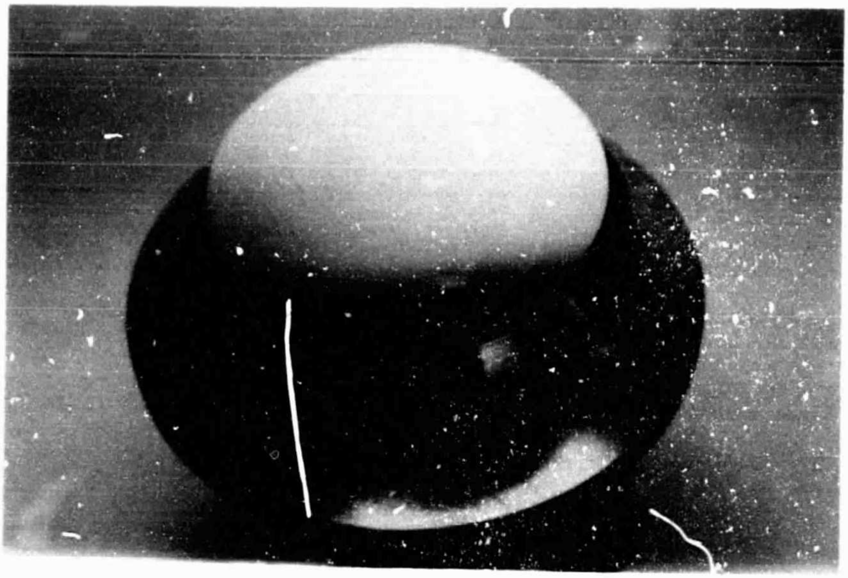

Figure 1. a) 3600 groove mm^{-1} diffraction grating on elastically-deformable substrate.

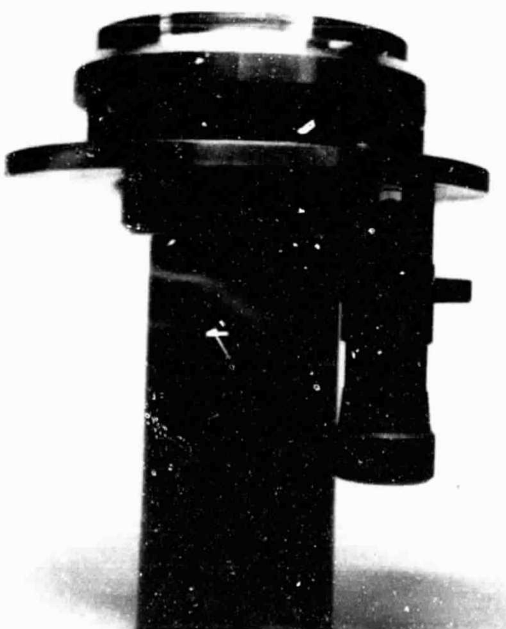

Figure 1. b) Substrate with deformation actuator.

In May of this year, Huber and Timothy made measurements of the aspect ratio of the toroidal surface of the grating using a Twyman-Green interferometer and also by observing the quality of the image in zeroth order at the appropriate angles of incidence and reflection. From the equation

$$R_v/R_h = \sin\alpha\cos\beta = \cos^2\gamma = 0.9782$$

for imaging with a 3600-groove-mm^{-1} grating in first order at wavelengths near 600 Å, $\alpha = 11.98°$ and $\beta = 0°$. Thus γ for zeroth order image tests = 8.49°. Measurements of the aspect ratio of the first toroidal grating by the two methods gave results which were in excellent agreement but which showed that the grating had been fabricated with an aspect ratio which was too large for stigmatic imaging near 600 Å. Huber's report of these tests is attached to this progress report. From discussions with B. Bach at Hyperfine, Inc., it became clear that the incorrect aspect ratio was the result of an improper setup at Hyperfine and not the result of a failure of the deformation and replication process.

During the past few weeks, a second replica grating has been fabricated by Hyperfine, Inc., and recent measurements by Huber in Zurich have shown that the aspect ratio of this grating is now within a few percent of the desired value. The initial measurements give an aspect ratio of 0.9809 as compared with the goal of 0.9782. Calculations show that the grating should have the desired imaging properties over the wavelength range from 462 to 609 Å. Additional measurements at visible wavelengths will be undertaken during the next few weeks, and the grating will then be sent to the University of Padua for the initial EUV tests. These will be carried out in the vacuum spectrograph which was designed to accommodate the toroidal grating and which is now set up in a

laboratory at the University of Padua. It is now our expectation that the initial EUV tests will be undertaken no later than the end of October of this year.

In parallel with these activities, an open-structure (256 x 1024)-pixel, Multi-Anode Microchannel Array (MAMA) detector system has been assembled. This detector has an active area of 6.5 x 26 mm^2 and pixel dimensions of 25 x 25 $microns^2$ (see Figure 2). A number of sealed ultraviolet and visible light MAMA detector tubes have also been fabricated and are being used to verify the imaging properties of this detector system. Distortion-free imaging with single-pixel resolution has been verified for the two-dimensional detector system as shown in Figure 3. Following the initial photographic tests of the toroidal grating, detailed measurements of the imaging properties will be undertaken using both visible-light and open-structure versions of the MAMA detector system. It is now expected that these tests will be undertaken in November and December of this year.

The toroidal diffraction grating and the open-structure imaging detector system now provide the means to verify the proof-of-concept of the spectroheliometer design. A proposal has accordingly been submitted to NASA for the continuation of this program through 1985 with the goal of completing the detailed definition of the EUV spectroheliometer configuration that is compatible with flight on the SPARTAN carrier.

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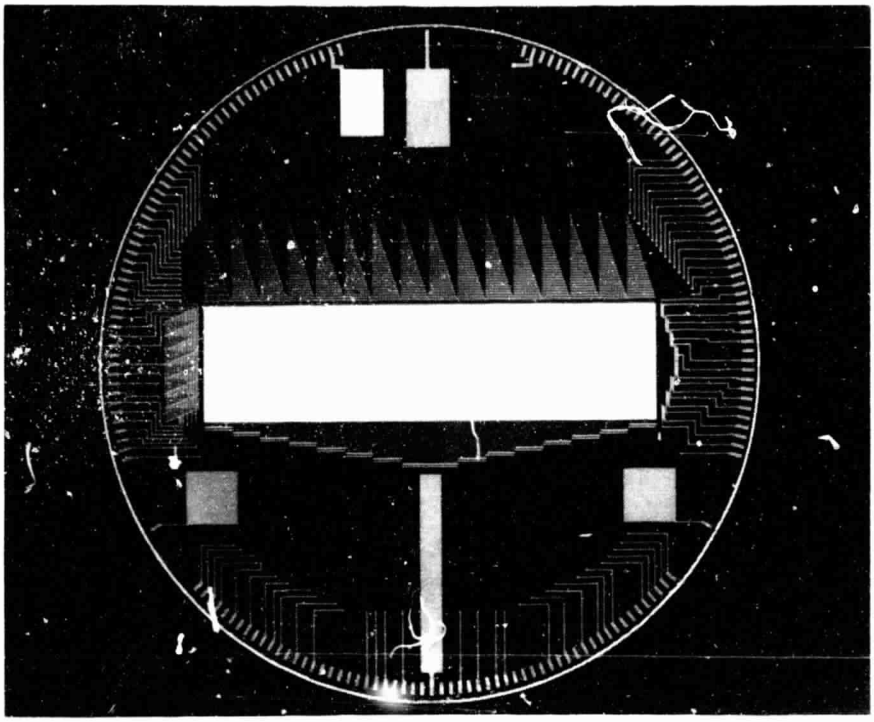

Figure 2. Readout array of (256 x 1024)-pixel MAMA detector with pixel dimensions of 25 x 25 microns^2.

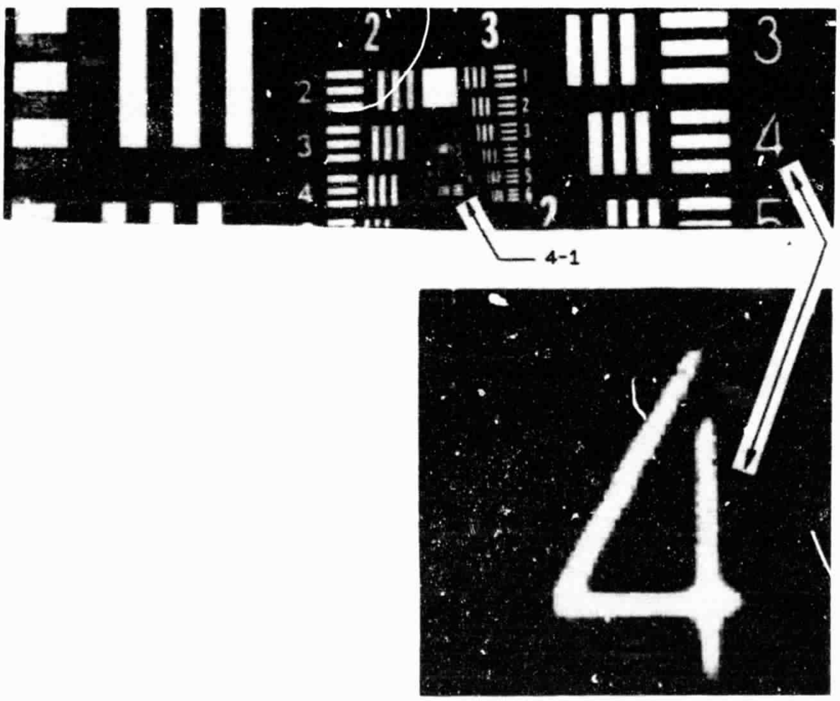

Figure 3. Ultraviolet image recorded with (256 x 1024)-pixel, pulse-counting MAMA detector system. Bar group 4-1 is ∿ 1-2 pixels wide.

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ATTACHMENT 1

Report on preliminary tests of Hyperfine grating No. 616 (3600 l/mm, "bent toroid", 1 m average radius of curvature, ruled surface 70 mm $\times$ 70 mm, Os coated)

Summary

MCEH AND JGT have made a first measurement of the aspect ratio of grating number 616 on May 19, 1984 at ETH Zurich. An interferometric test, which indicated an aspect ratio of 0.9892, was confirmed by a determination of the stigmatic focus in zero order. It was concluded that the deviation of the toroid from a sphere is about half of what it should be.

1. Determining the wavefront in a Twyman–Green interferometer

By use of the setup shown in Fig. 1, we compared the wavefront reflected by the toroidal grating with a spherical wavefront. The fringes trace contour lines, i.e. lines of equal height above or below a spherical surface. Going from one fringe to the next corresponds increasing (or decreasing) the height by $\lambda/2$ (with $\lambda = 0.6328\ \mu m$).

The measured height differences going from the center to the edges on the top (or bottom) and on the sides of the $70 \times 70\ mm^2$ aperture — was ca. $\pm$ 10.5 fringes. This corresponds to a height difference of

$$\pm\delta = \pm(\text{fringes} \times \lambda/2) = \pm(10.5 \times 0.6328/2) = \pm 3.32\ \mu m \tag{1.1}$$

or to a total height difference at the centers of the edges of

$$\Delta = h_v - h_h = 2\delta = 6.64\ \mu m. \tag{1.2}$$

We use the geometrical relations defined by Fig. 2 and obtain:

$$\Delta = h_v - h_h = \frac{a^2}{2}\left(\frac{1}{R_v} - \frac{1}{R_h}\right) = \frac{a^2}{2R^2}(R_h - R_v) = \frac{a^2}{2R}\left(1 - \frac{R_v}{R_h}\right) \tag{1.3}$$

where R is the (average) radius of the flexible grating in its spherical state. (It was assumed throughout that $h \ll R$, so that terms of the order of h^2 could be neglected and $R_v \cdot R_h = R^2$.) The indices h and v refer to the horizontal and vertical radii of curvature.

From the interferometric measurement we thus obtain the aspect ratio, which is given by equ. (1.3), but is derived differently as a check on the approximations used:

$$\begin{aligned} \frac{R_v}{R_h} &= \frac{R - \frac{R_h - R_v}{2}}{R + \frac{R_h - R_v}{2}} = \frac{R - \frac{R^2\Delta}{a^2}}{R + \frac{R^2\Delta}{a^2}} \simeq 1 - \frac{2R\Delta}{a^2} \\ &= 1 - \frac{2 \times 10^3\mathrm{mm} \times 6.64 \times 10^{-3}\mathrm{mm}}{35^2\mathrm{mm}^2} = 0.9892 \end{aligned} \tag{1.4}$$

2. Determining the stigmatic condition in zero order.

The condition for stigmatic imaging with a toroidal grating is

$$\frac{R_v}{R_h} = \cos\alpha \cdot \cos\beta_0 = \cos^2\gamma \tag{2.1}$$

where α and β_0 are the angles of incidence and diffraction, respectively, that apply for a stigmatic focus. For the special case of zero order, $\alpha = \gamma$ and $\beta_0 = -\gamma$.

To check the interferometric measurement, we determined the lateral distance $b = 187$ mm between the (point) light source and the stigmatic focus in zero order. Before this measurement, the grating had been set at an angle of incidence and reflection so that a stigmatic focus indeed occured. The measured angle $\gamma = \arcsin\frac{b}{2R} = \arcsin\frac{187\,\mathrm{mm}}{2 \times 10^3\mathrm{mm}} = 5^\circ.4$ then resulted in the aspect ratio

$$\frac{R_v}{R_h} = \cos^2(5^\circ.4) = 0.991 \tag{2.2}$$

This measurement yields a total height difference at the centers of the edges.

$$\Delta = \frac{a^2}{2R}(1 - \frac{R_v}{R_h}) = \frac{35^2\,\mathrm{mm}^2}{2 \times 10^3\,\mathrm{mm}}(1 - 0.991) = 5.5\,\mu\mathrm{m}. \tag{2.3}$$

It should be stressed however, that this second measurement is not as accurate as the interferometric one. It served only to confirm the order of magnitude of the first one (to exclude an error by a factor of two in Δ, for example).

3. Stigmatic wavelengths of present grating

The wavelengths for stigmatic conditions that are available with the present grating can be calculated from equ. (2.1) and the grating equation

$$n\lambda = d(\sin\alpha + \sin\beta_0) \tag{3.1}$$

where the order is assumed to be $n = 1$ and the grating constant is $d = 2777.8$ Å.

With the vacuum spectrograph in Padova, which has been prepared for the grating tests, the angle $\vartheta = \alpha + \beta_0$ between incident and diffracted beam should probably be 12° as a minimum. The maximum angle ϑ that can be reached with the present aspect ratio is about 11°.9, and the corresponding maximum stigmatic wavelength is then $\lambda(\alpha = 5^\circ.9, \beta_0 = 6^\circ) \simeq$ 577 Å. Maybe this can still be reached with photographic tests.

If the blur at the central wavelength $\lambda(\beta = 0^\circ)$ should not exceed 25 μm (i.e. one pixel of the present MAMA detector) we must chose $|\beta_0| \leq 1^\circ.52$. This results in a $\vartheta_{max} \leq \alpha + \beta_0 = 8^\circ.29 + 1^\circ.52 \leq 9^\circ.81$. The wavelengths at the upper limit of $|\beta_0|$ are

$$\begin{aligned} \lambda(\beta_0 &= -1^\circ.52) = 327\,\text{Å} \\ \lambda(\beta &= +0^\circ.00) = 401\,\text{Å} \\ \lambda(\beta_0 &= +1^\circ.52) = 474\,\text{Å} \end{aligned} \tag{3.2}$$

For $\beta_0 = 0$ we obtain $\vartheta = 8^\circ.43$ and

$$\lambda(\beta_0 = +0^\circ.00) = 407\,\text{Å} \tag{3.3}$$

4. Setting for zero order for the specified aspect ratio $R_v/R_h = 0.9782$.

The specified aspect ratio $R_v/R_h = 0.9782$ results in an angle of incidence and of reflection of $\gamma = 8^\circ.4907$ for zero order condition and thus in a lateral distance between light source and stigmatic image of

$$b = 2R_h \sin\gamma = 2 \times 1011.1 \text{ mm} \times \sin\gamma = 298.6 \text{ mm}. \qquad (4.1)$$

Such a setup and angle γ could in principle be used for setting the distortion of the flexible blank. (When the present grating (No. 616) is used in zero order at this angle, a marked astigmatism is observed, as expected with the present value for the aspect ratio.)

Fig. 1 Twyman-Green Interferometer

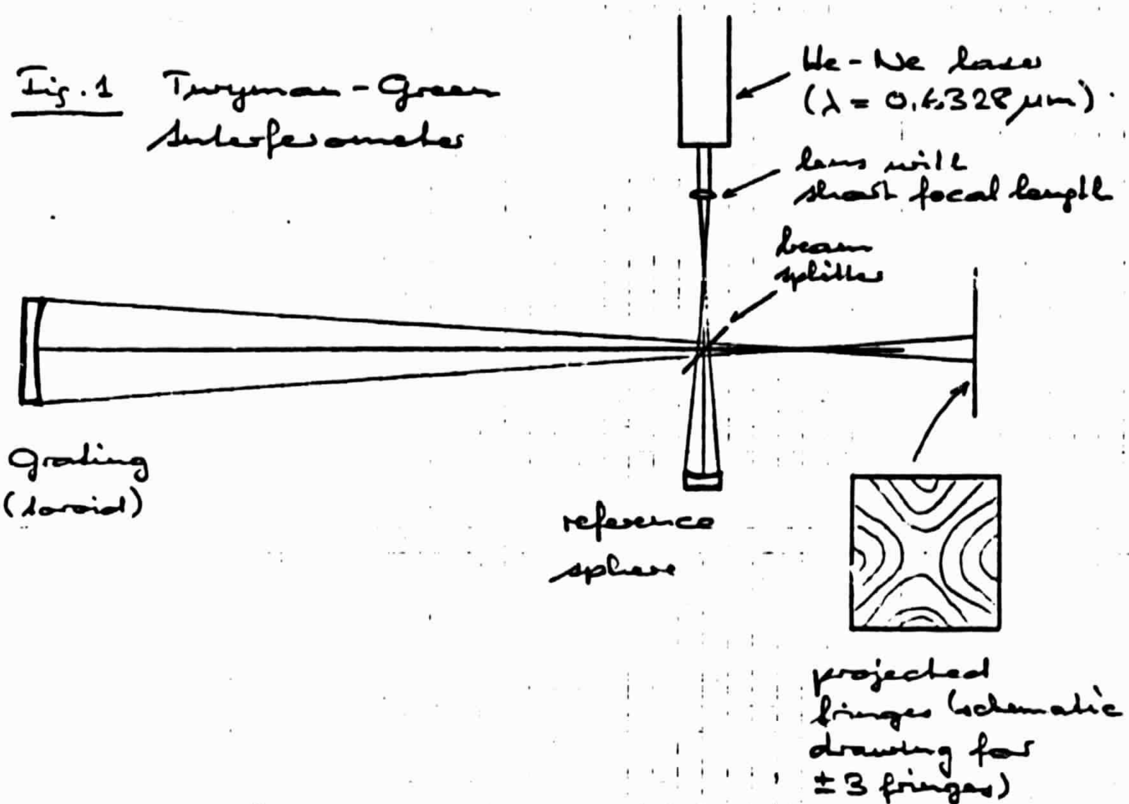
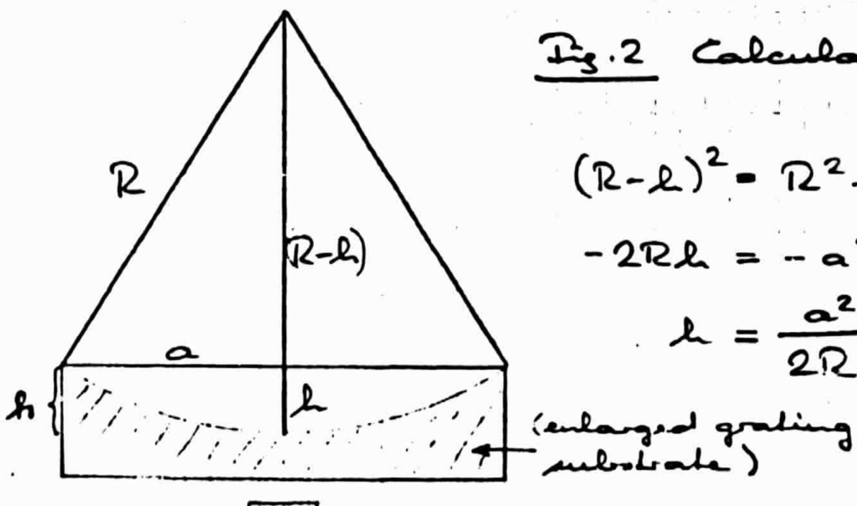


Fig. 2 Calculating h

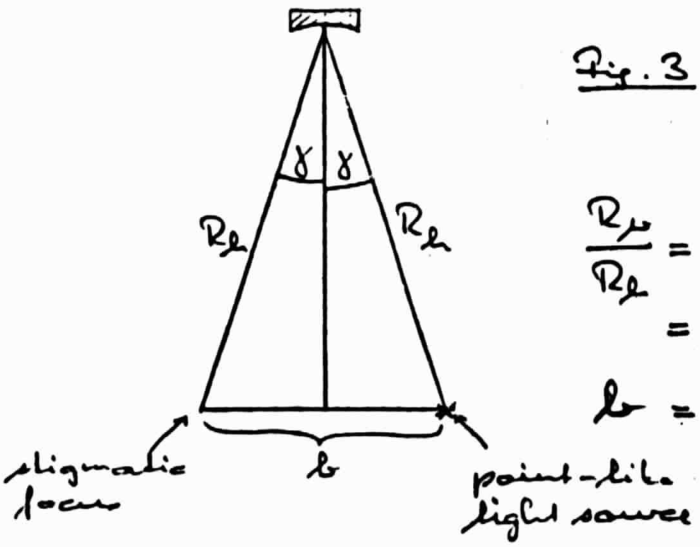


$$(R-h)^2 = R^2 - a^2$$

$$-2Rh = -a^2$$

$$h = \frac{a^2}{2R}$$

Fig. 3 Stigmatic focus in zero order.



$$\frac{R_v}{R_h} = \cos\gamma \cdot \cos(-\gamma) =$$

$$= \cos^2\gamma$$

$$b = 2R_h \sin\gamma$$